Status of $W^{\pm}$ Boson Production Measurements at PHENIX

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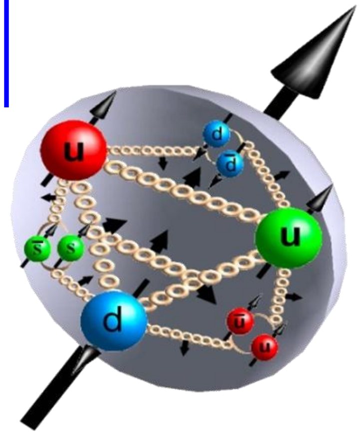
BNL Nuclear Physics Seminar
May 28, 2013

Outline

- Introduction
- PHENIX Detector Overview
- Mid-rapidity W Measurements
- Forward rapidity W Measurements
- Future Prospects
- Summary

Proton Spin Puzzle



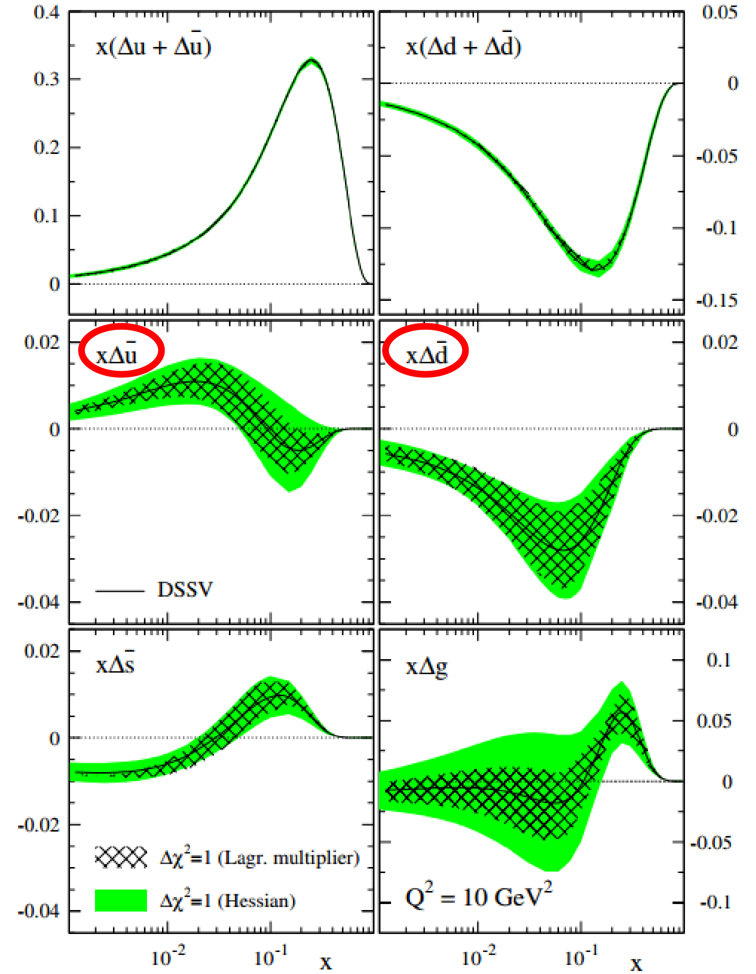
$$\langle S_p \rangle = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

quark polarization well measured in DIS: ~30%

$$\Delta\Sigma = \int dx(\Delta u + \Delta d + \Delta s + \Delta\bar{u} + \Delta\bar{d} + \Delta\bar{s})$$

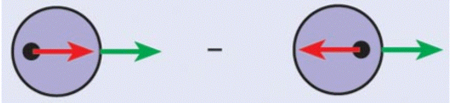
Sea anti-quark polarization not well constrained in SIDIS

DSSV Global Analysis:
Phys. Rev. D 80, 034030 (2009)



Polarized parton distribution functions (PDF):

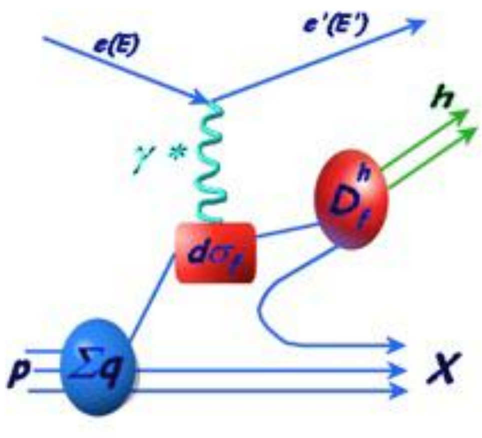
$$\Delta q_i(x) = q_i^+(x) - q_i^-(x)$$



Sea Quark Polarization

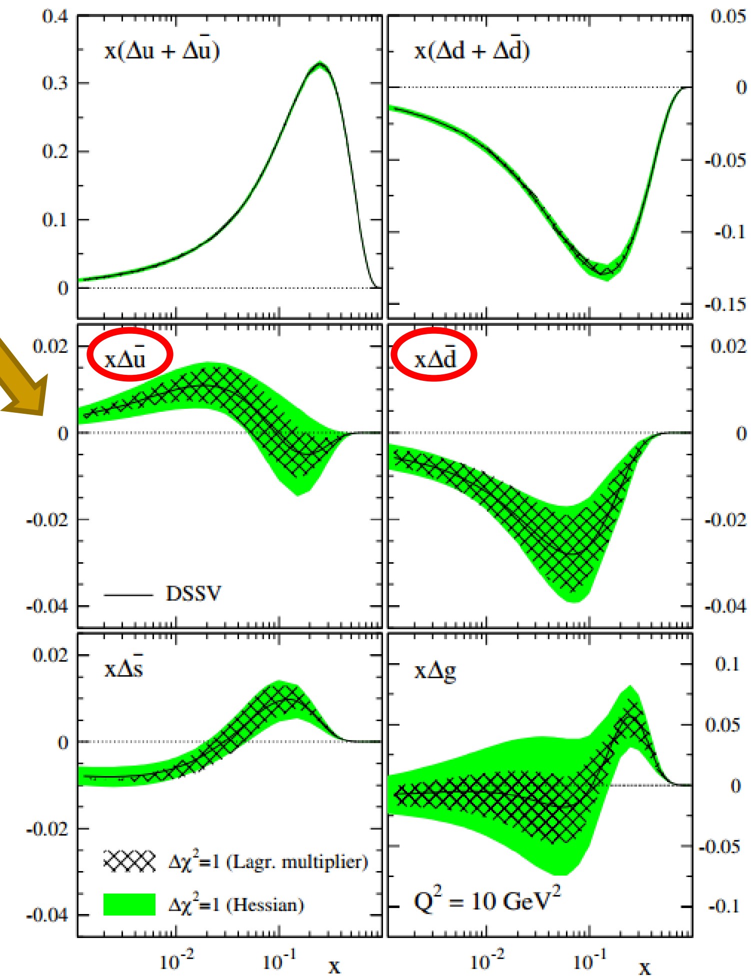
Polarized Semi-Inclusive DIS (SIDIS) measurements (SMC, HERMES, COMPASS) constrained flavor-separated polarized PDFs

SIDIS results depend on fragmentation processes:



=> SIDIS results limited by large uncertainties of fragmentation functions

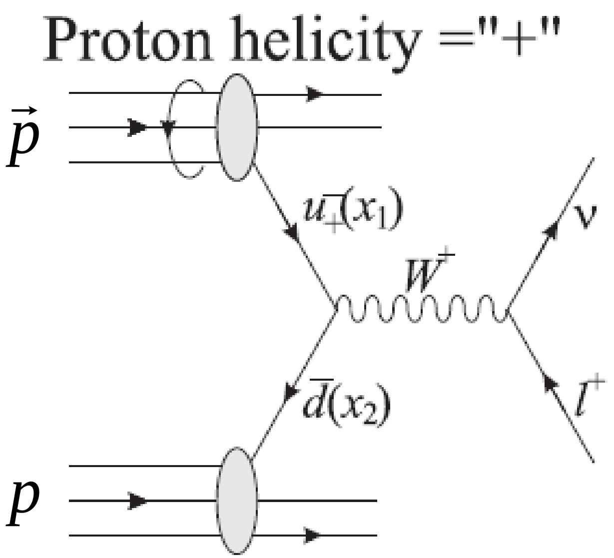
DSSV Global Analysis:
Phys. Rev. D 80, 034030 (2009)



$W^{\pm}$ Boson Production in Polarized Proton Collisions

To measure $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$ PHENIX exploits maximal-parity violation in W production in longitudinally polarized p+p collisions

W^{+} production example at LO:



$$u+\bar{d}\rightarrow W^{+}\rightarrow \ell^{+}+\nu$$

$$d+\bar{u}\rightarrow W^{-}\rightarrow \ell^{-}+\nu$$

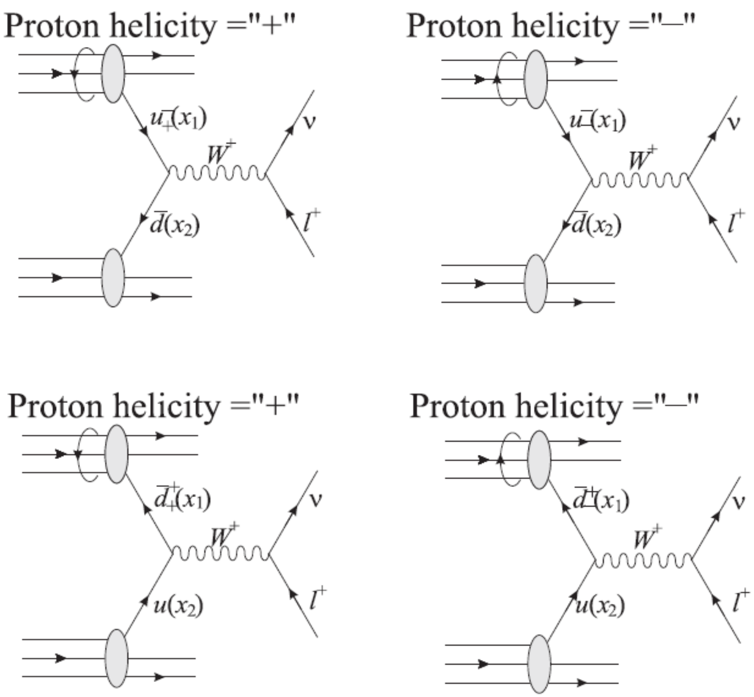
- No uncertainty from fragmentation: Ws detected through their leptonic decay channels
- Ws couple directly to the quarks and antiquarks

- Parity violation in the electroweak interaction allow perfect quark/antiquark helicity separation: only left-handed quarks and right-handed anti-quarks are selected

Parity Violating Single-spin Asymmetry A_L

Flipping the spin orientation of one of the colliding protons and averaging over another:

$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$



$$A_L^{W^+} = \frac{u_+^-(x_1)\bar{d}(x_2) - u_-^-(x_1)\bar{d}(x_2)}{u_+^-(x_1)\bar{d}(x_2) + u_-^-(x_1)\bar{d}(x_2)} = -\frac{\Delta u(x_1)}{u(x_1)}$$

$$+$$

$$A_L^{W^+} = \frac{\bar{d}_+^+(x_1)u(x_2) - \bar{d}_-^+(x_1)u(x_2)}{\bar{d}_+^+(x_1)u(x_2) + \bar{d}_-^+(x_1)u(x_2)} = \frac{\Delta\bar{d}(x_1)}{\bar{d}(x_1)}$$

$$\Downarrow$$

$$A_L^{W^+} = -\frac{\Delta u(x_1)\bar{d}(x_2) - \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$$

$$A_L^{W^-} = -\frac{\Delta d(x_1)\bar{u}(x_2) - \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)}$$

Flavor-Separated Quark Polarized PDFs at PHENIX

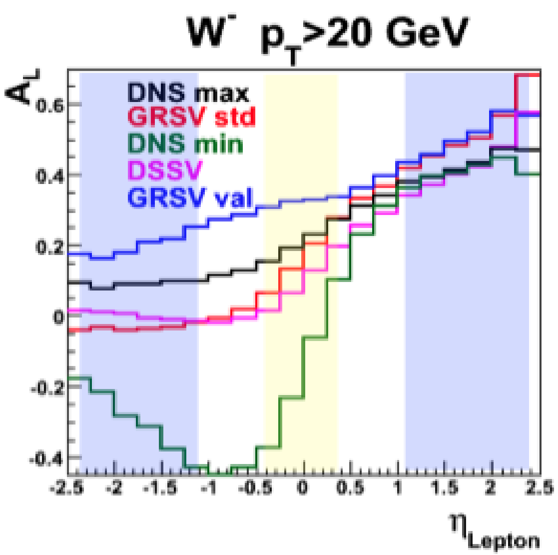
$\langle x_1 \rangle >> \langle x_2 \rangle : \quad A_L^{W^+} \approx -\frac{\Delta u}{u}$ (forward rapidity)

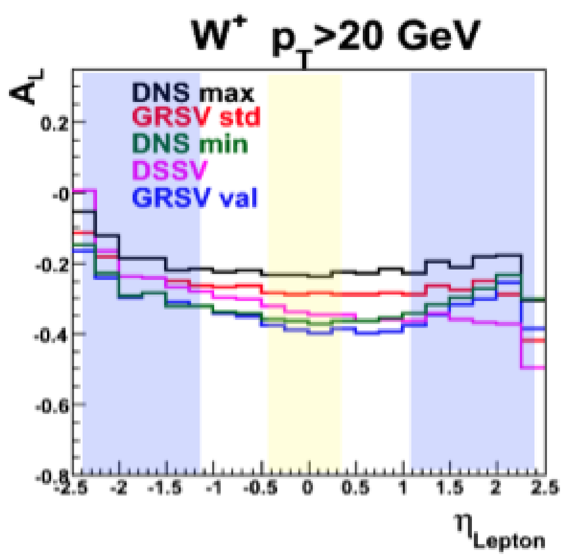
$\langle x_1 \rangle << \langle x_2 \rangle : \quad A_L^{W^+} \approx \frac{\Delta \bar{d}}{\bar{d}}$ (backward rapidity)

$\langle x_1 \rangle >> \langle x_2 \rangle : \quad A_L^{W^-} \approx \frac{\Delta d}{d}$ (forward rapidity)

$\langle x_1 \rangle << \langle x_2 \rangle : \quad A_L^{W^-} \approx \frac{\Delta \bar{u}}{\bar{u}}$ (backward rapidity)

PHENIX Muon Arms (forward/backward rapidities) measuring the different quark flavor distributions





PHENIX Central Arm (mid-rapidity) measuring the mixture of quark flavor contribution:

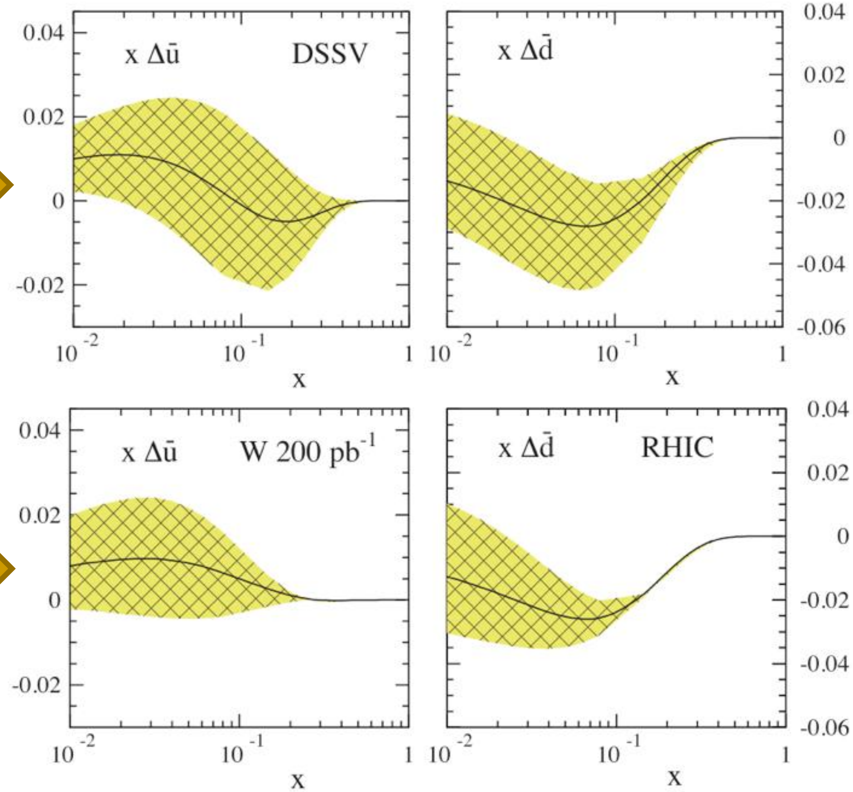
- For W^+, combination of Δu and $\Delta \bar{d}$
- For W^-, combination of $\Delta \bar{u}$ and Δd

Impact of A_L measured at RHIC

Phys. Rev. D 81, 094020 (2010)

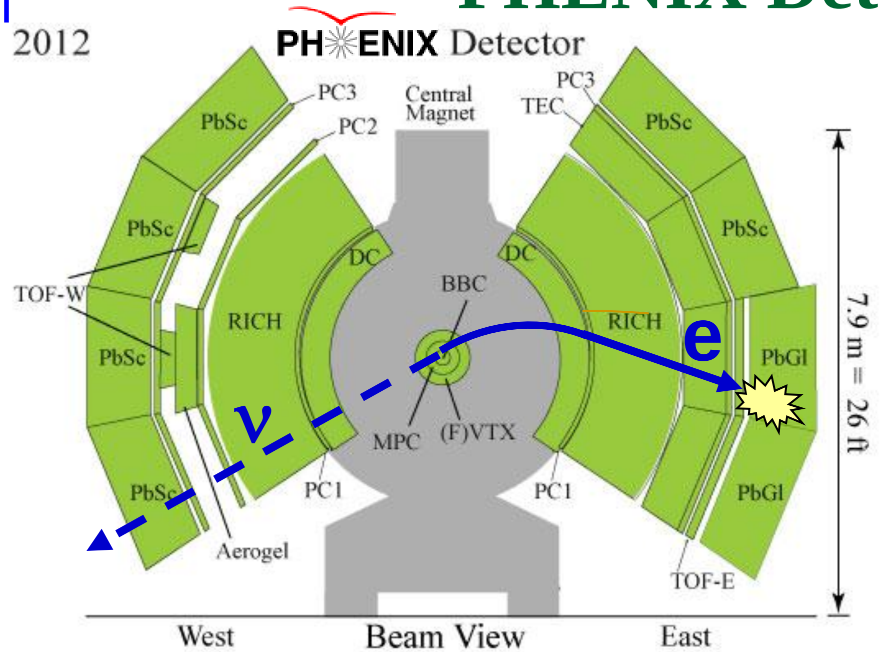
DSSV global analysis

DSSV global analysis
+ simulated 200 pb^{-1}
W A_L at proton-proton collisions in RHIC



Significant impact for reducing uncertainties

PHENIX Detector Overview

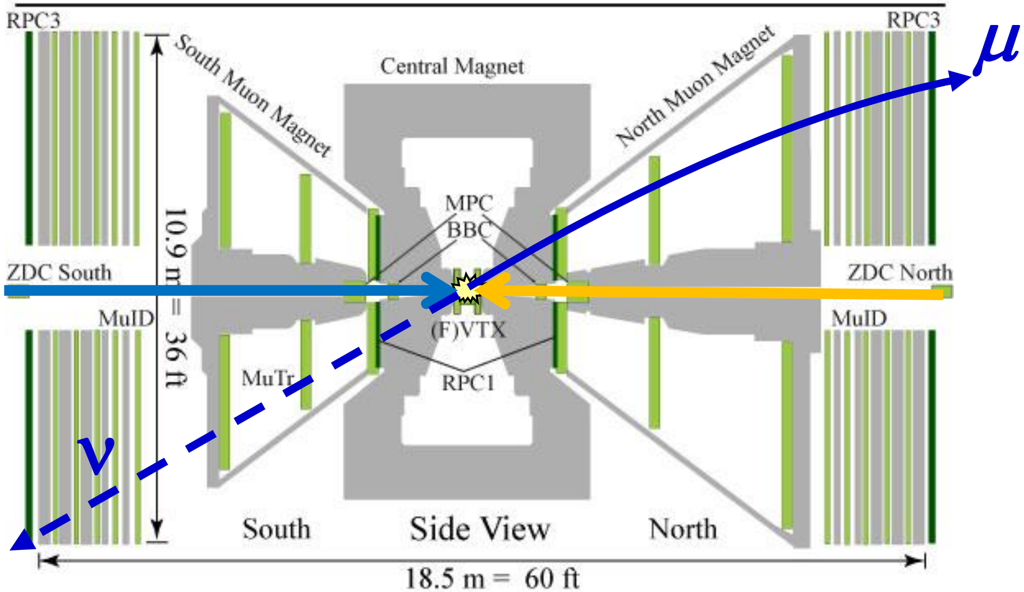


$$p + p \to W^{\pm} \to e^{\pm} + \nu$$

(mid-rapidity)

Central arm spectrometers:

- 2 arms: $|\eta|<0.35$, each $\Delta\phi = \pi/2$
- Electromagnetic Calorimeter (EMCal: PbSc, PbGl): triggering
- Drift Chamber (DC) and Pad Chamber (PC): tracking charged tracks
- Axial B Field



$$p + p \to W^{\pm} \to \mu^{\pm} + \nu$$

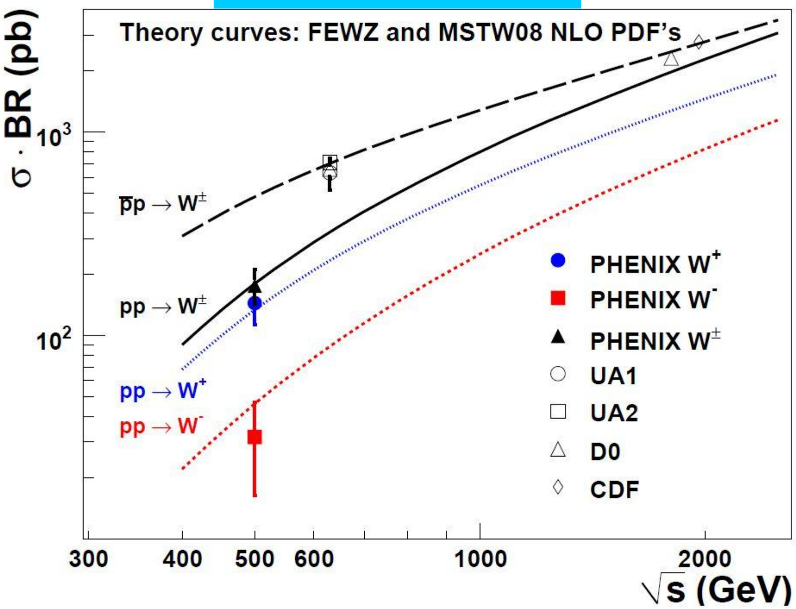
Forward (Muon) arm spectrometers:

- $1.2 < \eta < 2.4$ (North)
  $-2.2 < \eta < -1.2$ (South), $\Delta\phi = 2\pi$
- Muon Tracker (MuTr): tracking, triggering
- Muon Identifier (MuID): particle ID, triggering
- Resistive Plate Chamber (RPC): particle ID, triggering
- Radial B Field

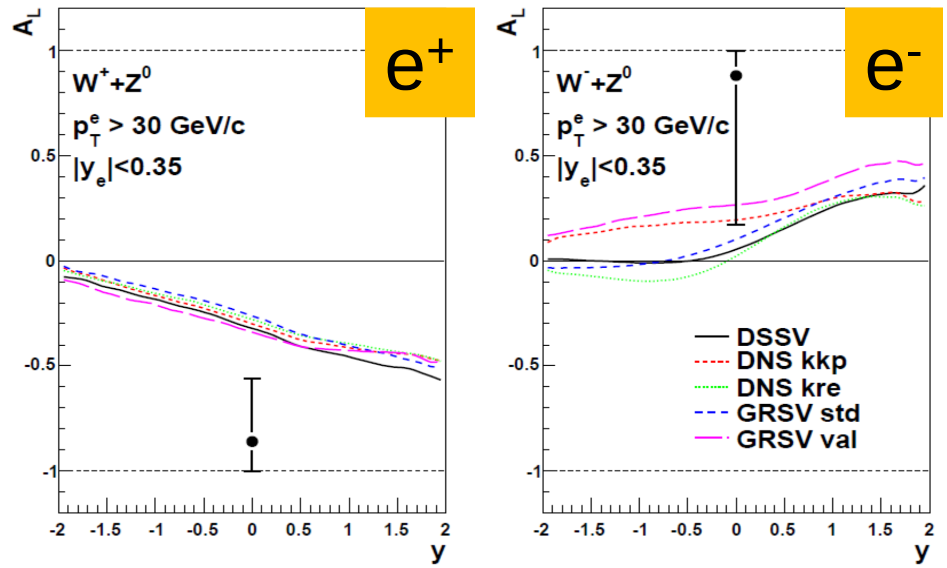
PHENIX Run 2009 W± measurements

First W measurements in 500 GeV longitudinally polarized p+p collisions in Central Arm at mid-rapidity

Cross section



A_L

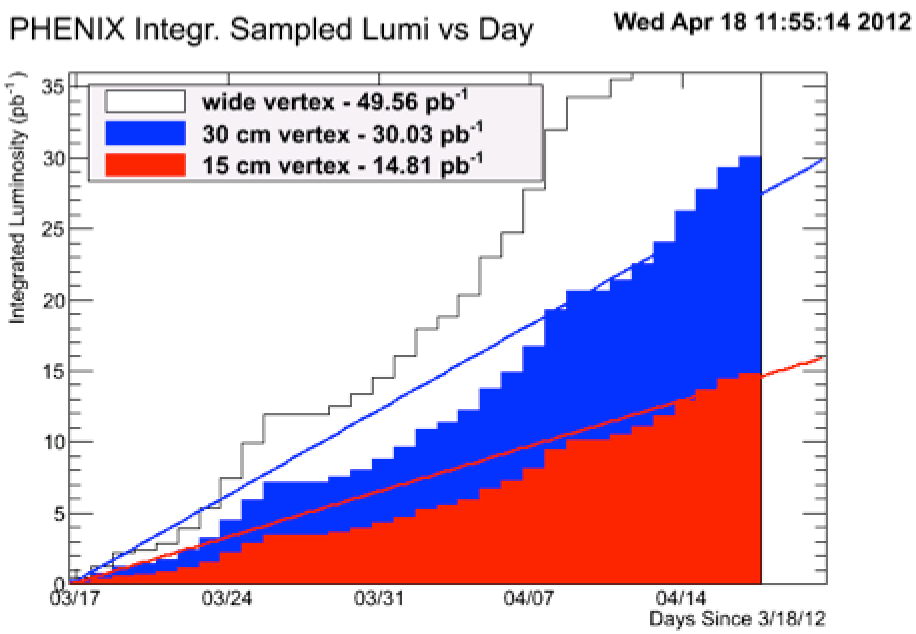


Phys. Rev. Lett. 106, 062001(2011)

PHENIX Run 2012 Dataset

Year	√s (GeV)	∫Ldt (pb^{-1})	Pol. (%)	P^2L (pb^{-1})
2009	500	8.6	39	1.3
2011	500	16	48	3.7
2012	**510**	**30**	**55**	**9.1**

(Note: recorded luminosity within |z-vertex|<30 cm)



In Run 2012 510 GeV longitudinally polarized p+p collisions, PHENIX recorded larger data sample with improved polarization in comparison to Run 2011 and Run 2009

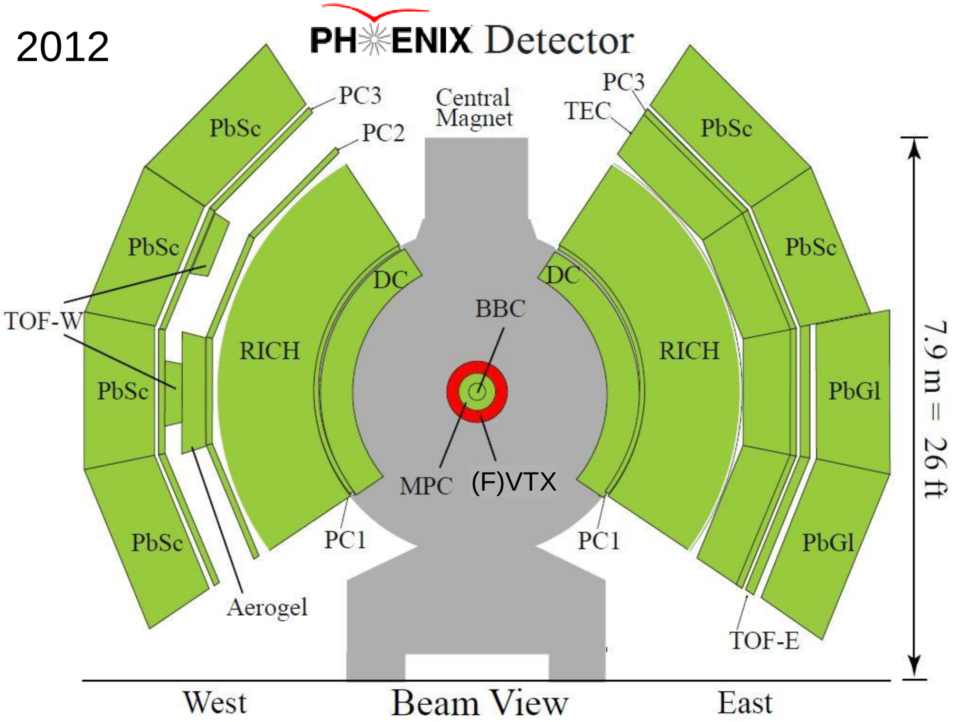
Mid-rapidity W Measurements

|η|<0.35

$$p + p \rightarrow W^{\pm} \rightarrow e^{\pm} + \nu$$

PHENIX Central Arm Spectrometers

2012



- 2 arms: each $\Delta\phi = \pi/2$
- $|\eta|<0.35$ in rapidity
- Vertex cut : $|z| < 30$ cm

- Electromagnetic Calorimeter (EMCal: PbSc, PbGl) with fine segmentation $\Delta\varphi\text{x}\Delta\eta\sim0.01\text{x}0.01$
- EMCal calibrated with $M_{\gamma\gamma}$ of π^0 at high p_T
- Tracking and charge separation: Charged tracks measured in Drift Chamber (DC) and Pad Chamber (PC)
- VTX detector (commissioned in 2011)
- Axial B Field 0.78 Tesla-meters

Find the Ws

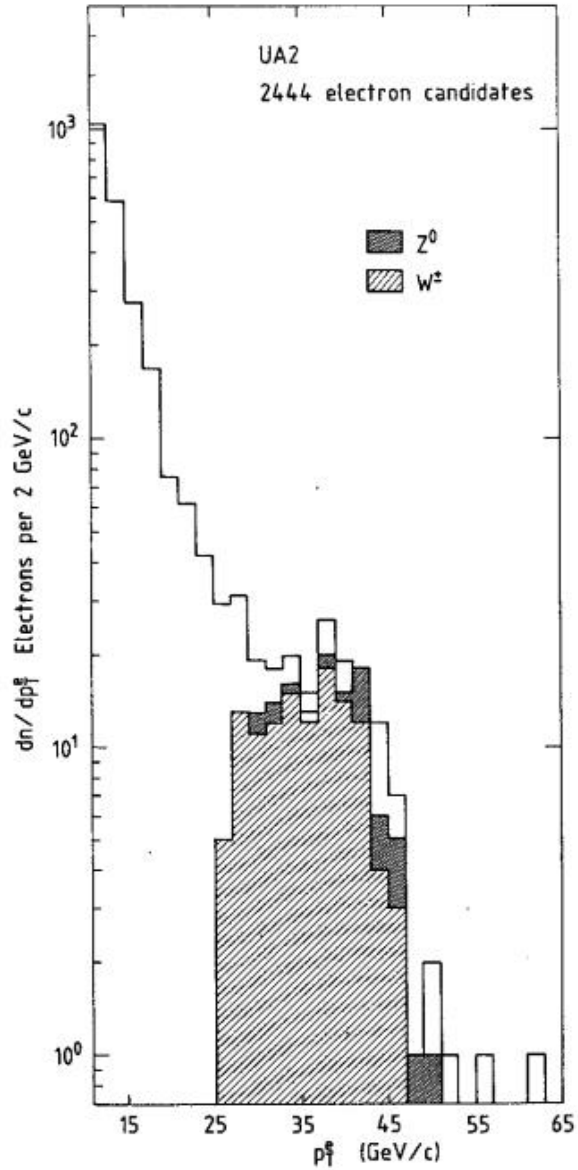
- Non-hermetic coverage => we can only identify $e^{\pm}$, no "missing energy" to balance

- => Can't identify $W^{\pm} \to e^{\pm} + \nu$ definitively on event-by-event basis

- Like UA1 and UA2 : looking for excess of events above background

W^{+} and W^{-} signal:

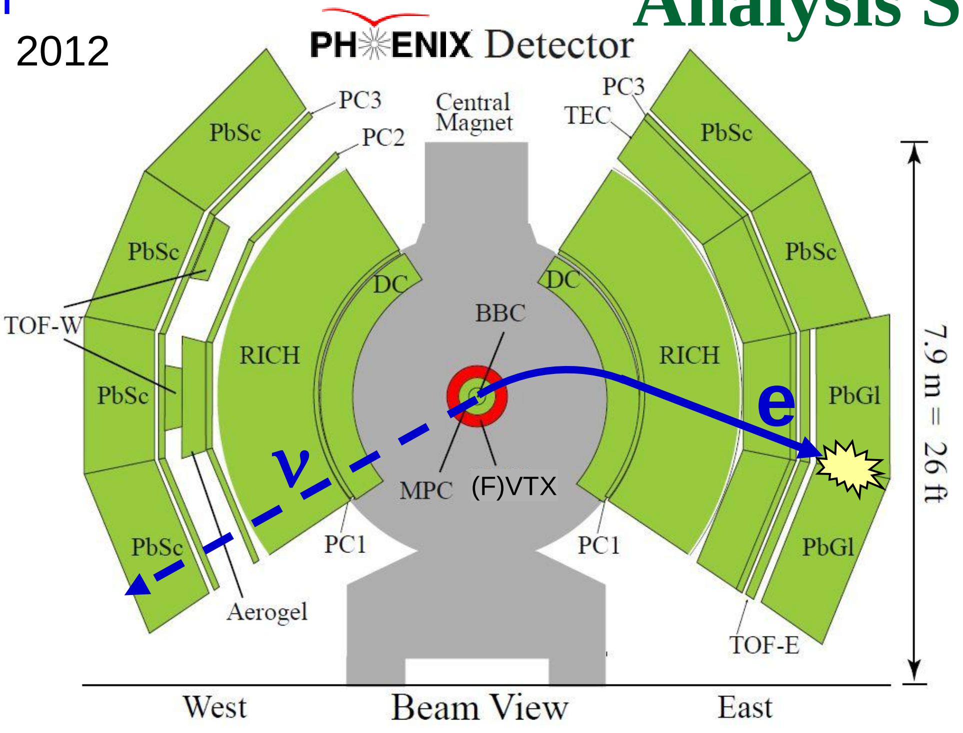
Jacobian peak at ~$M_W/2$



~$M_W/2$

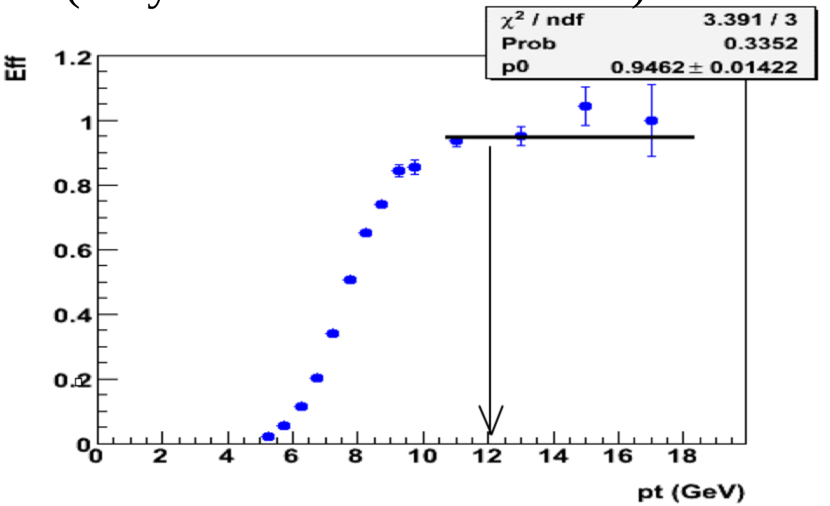
Analysis Strategy

2012

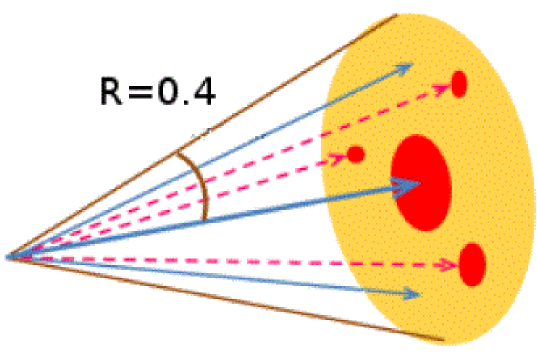


Detect high energy $e^{\pm}$ in the Central Arms:

- Trigger: EMCal 4x4 Tower Sum (fully efficient above 12 GeV)



- High energy EMCal clusters matched to charged tracks in DC for charge determination ($\Delta\phi < 0.01$ rad)

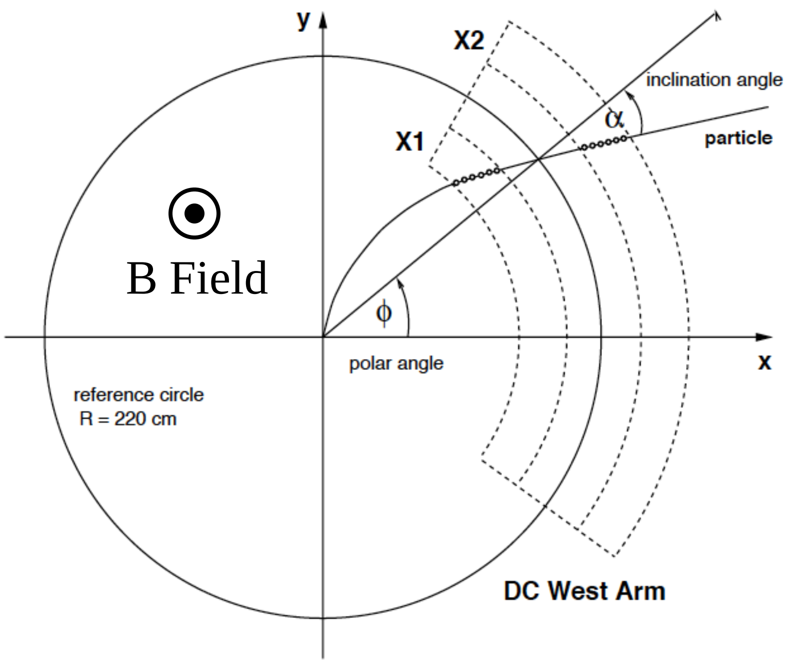


- **Isolation cut is the main background reducer**:

$$\frac{\text{energy in a cone of } R = 0.4 \text{ excluding the candidate cluster energy}}{\text{energy of the } e^{\pm} \text{ candidate}} < 10\%$$

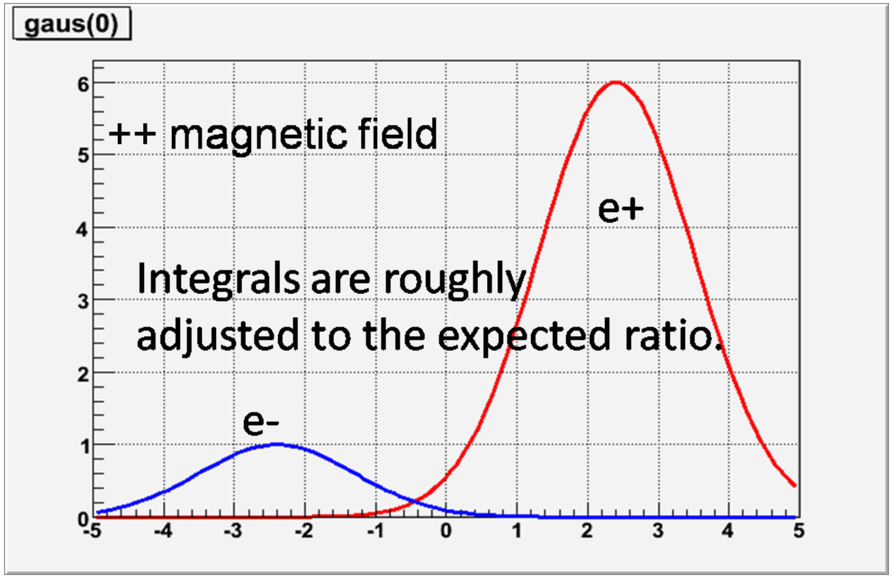
Charge separation: e^+ or e^-

- Momentum and charge determined in DC



- Angle at DC wrt infinite momentum track:
  $\alpha \approx 100$ mrad / q×P[GeV/c]
- 40 GeV/c track ⇒ $\alpha \approx 2.5$ mrad,

$\delta\alpha \approx 1.1$ mrad:



- Acceptance cuts on DC: remove tracks too close to wires to resolve L/R ambiguities (10%)
- Cut on DC tracks $|\alpha| < 1$ mrad to reduce charge mis-identification

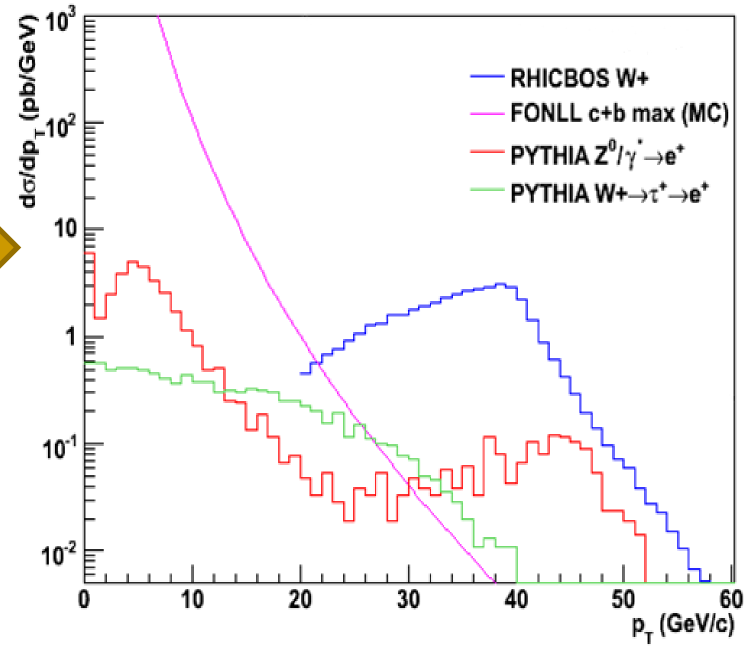
⇒ Charge sign determined with high confidence

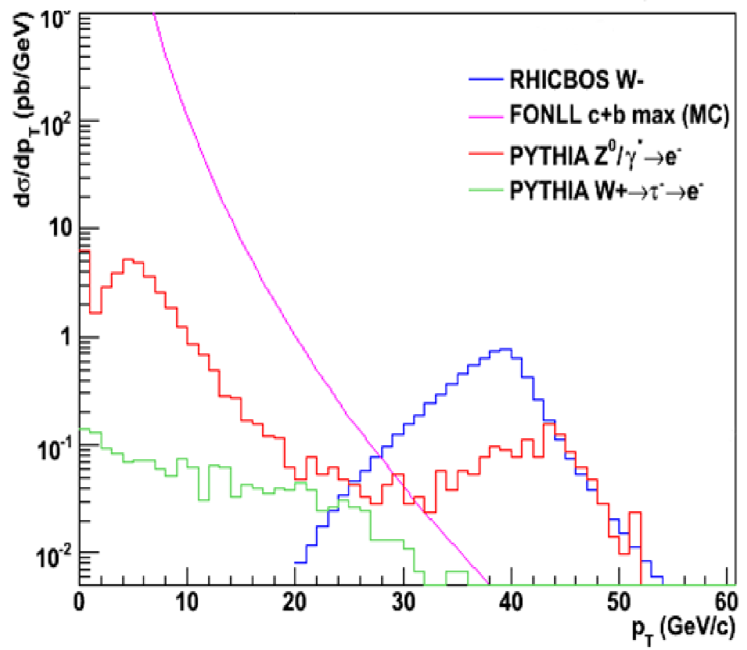
Background components

✓ Irreducible Backgrounds (pass cuts)
- c/b decays to $e^{\pm} + X$ relatively small above 30 GeV
- $W \to \tau \to e$ is also small
- $Z \to e^{+} + e^{-}$ is part of the signal

✓ Reducible Backgrounds
- Cosmic rays
- Beam related backgrounds
- Photon conversions $\gamma \to e^{+}e^{-}$ (before DC):

VTX Detector increases photon conversion background (radiation length =13.5%)

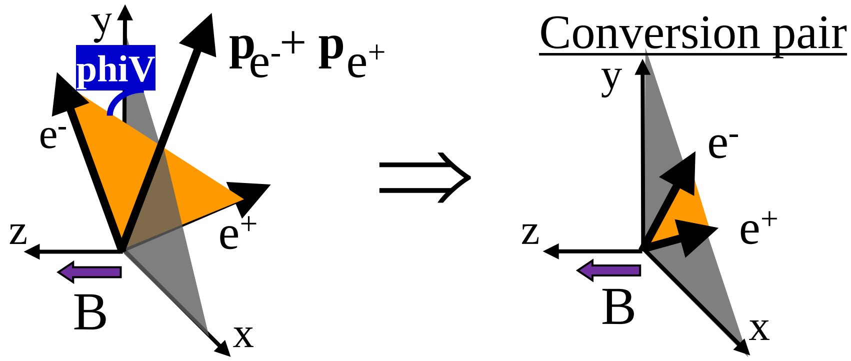


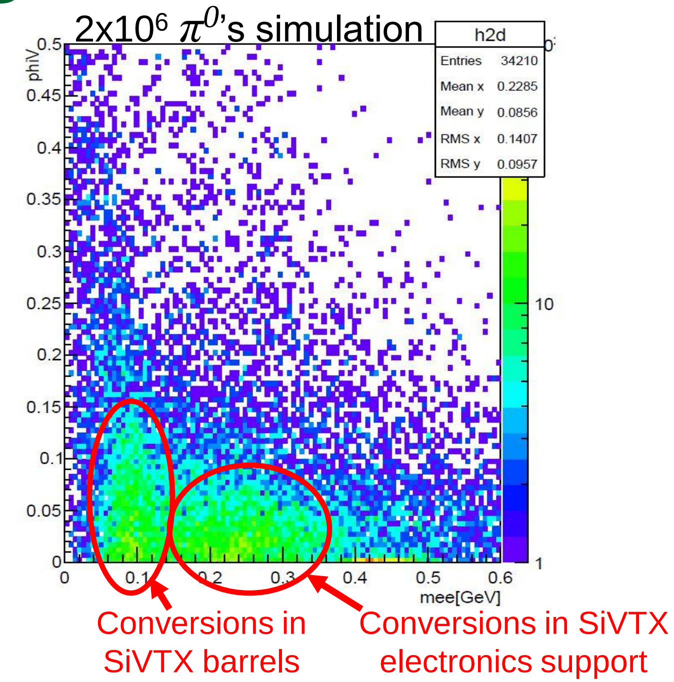


Detailed simulation study is in progress to estimate carefully the QCD background and background from the VTX conversions – this will let us to proceed with the W± cross-section measurements for Run 2012 and will result in improved background estimation overall in the analysis (including asymmetry measurements)

VTX conversion background

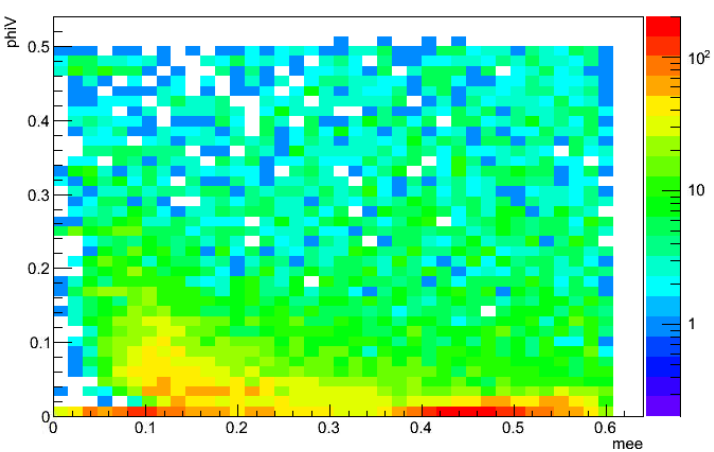
- orientation angle of the e^+e^- pair in the magnetic field (**phiV**) vs. apparent invariant mass $\mathbf{m_{ee}}$



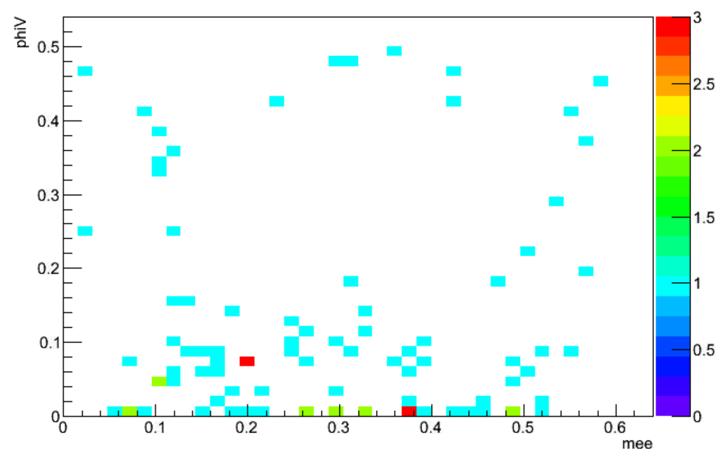


Isolation cut reduces effectively identified conversions:

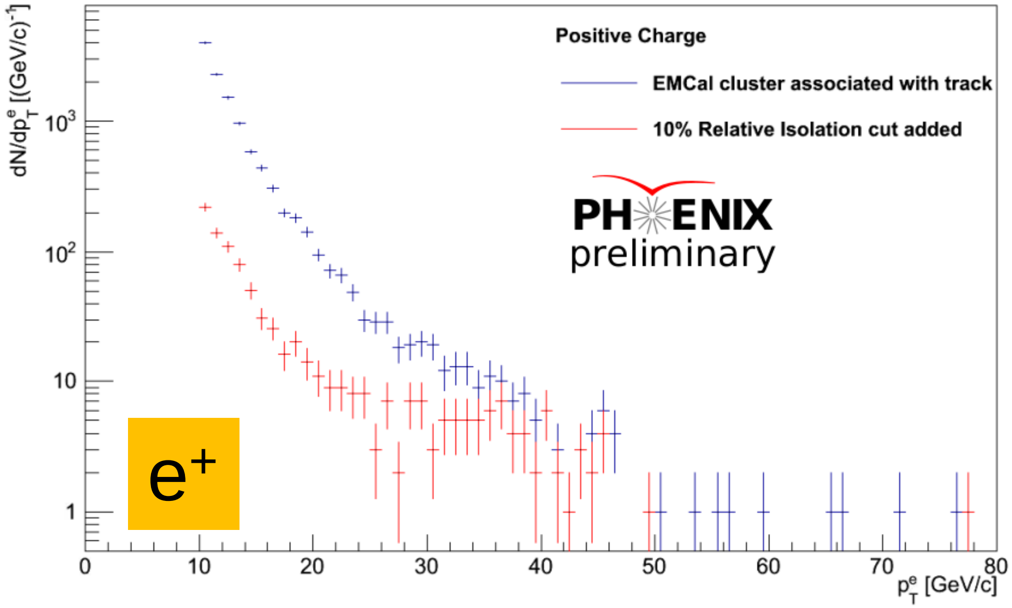
Before Isolation Cut

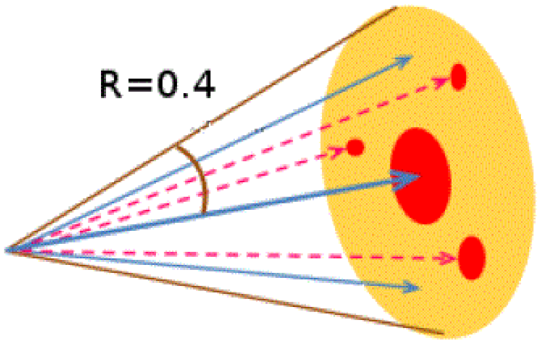


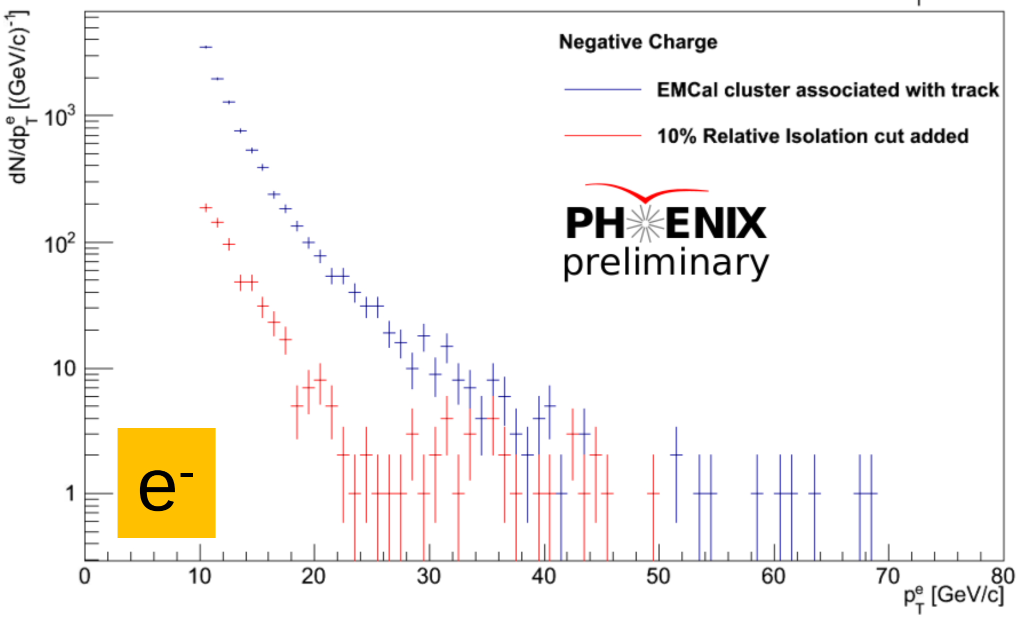
After Isolation Cut



Isolation cut effect on our spectrum







The relative isolation cut removes more than a factor of 10 in the background dominated region (10-20 GeV) while leaving the signal region (30-50 GeV) relatively untouched

Run 2012 Measured W^+ and W^- Spectra (Mid-rapidity)

- 30-50 GeV/c – Signal Region
- 10-20 GeV/c – Background Dominated

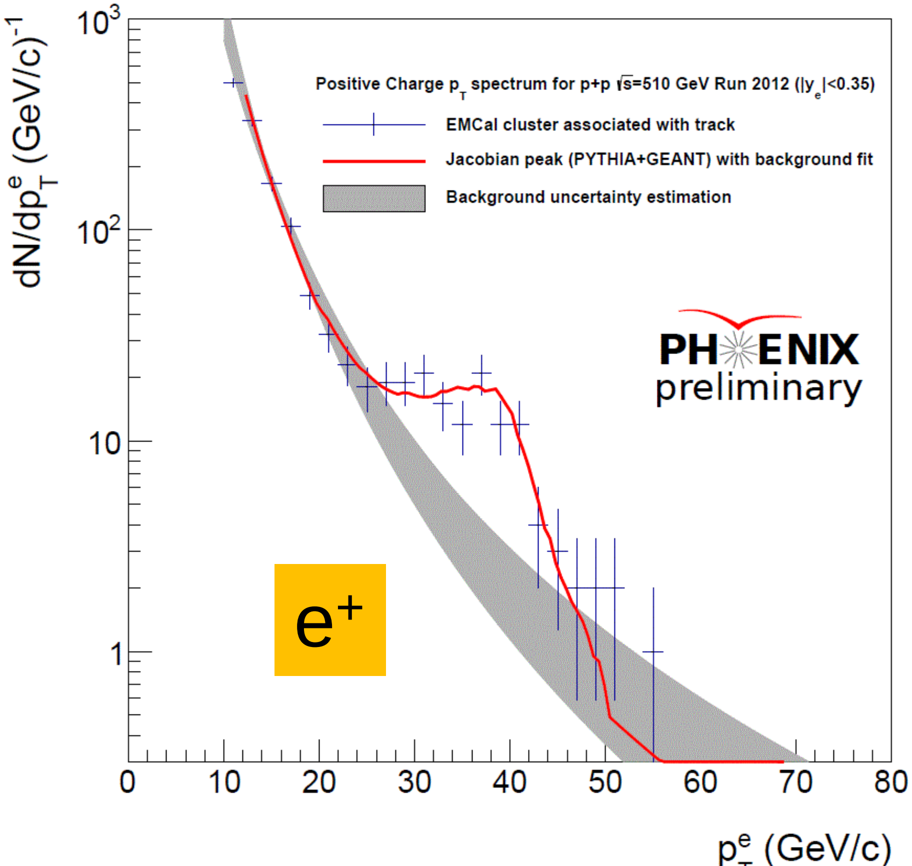
W^+ and W^- signal:

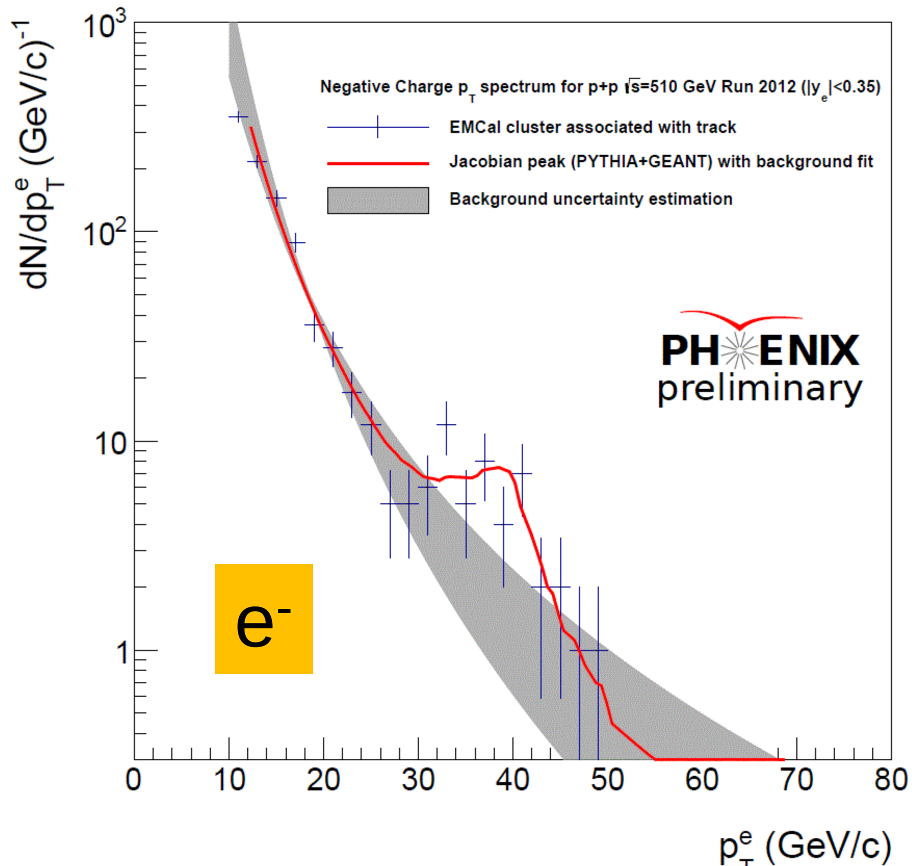
Jacobian peaks

- Background estimation:

Fit region 10 to 69 GeV/c with a power law

Fit region 20 to 50 GeV/c with a power law + Jacobian peak (simulation)





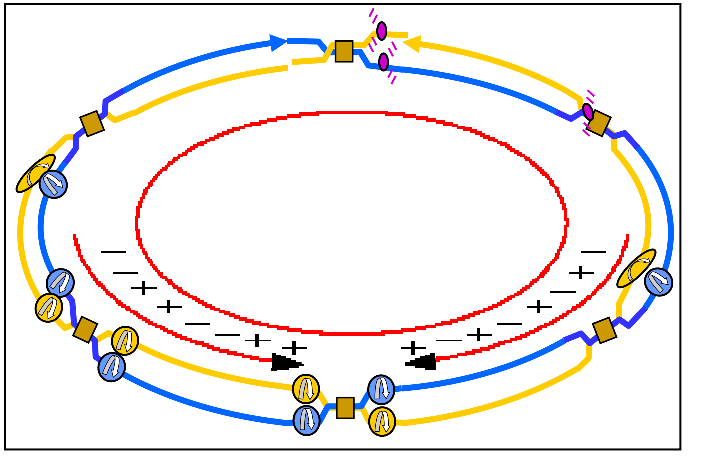
- After all cuts, we have 25% background in the signal region for W^+
- After all cuts, we have 42% background in the signal region for W^-

Single-Spin Asymmetry A_L Measurement

$$A_L^W \equiv \frac{\sigma(\overrightarrow{p}p \Rightarrow W) - \sigma(\overleftarrow{p}p \Rightarrow W)}{\sigma(\overrightarrow{p}p \Rightarrow W) + \sigma(\overleftarrow{p}p \Rightarrow W)}$$

$$\approx \frac{1}{P} \frac{N^+(e)/\mathcal{L}^+ - N^-(e)/\mathcal{L}^-}{N^+(e)/\mathcal{L}^+ + N^-(e)/\mathcal{L}^-}$$

N is the electron yield,
L is integarted luminosity,
P is luminosity-weighted polarization

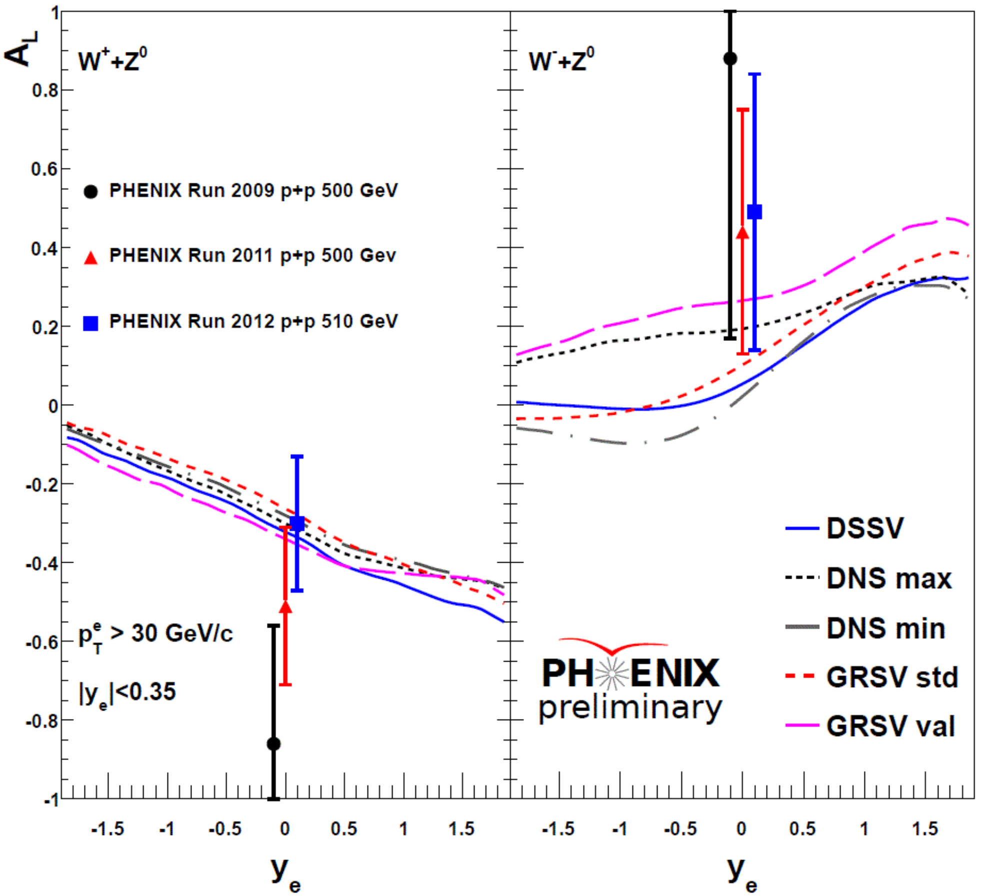


- ✓ At RHIC, up to 120 bunches in each ring, crossing every 106 ns, helicity of pairs ++,+−,−+,−− alternates rapidly
- ✓ Get one measurement treating “blue” beam as polarized, averaging over “yellow” beam
- ✓ Get second measurement treating yellow beam as polarized, averaging over blue beam
- ✓ Ideally we’d do this as function of $\eta(e)$ but statistics are limited
- ✓ Asymmetry in background region (10-20 GeV/c) consistent with 0: 0.025±0.09

Run 2012 W$^{\pm}$ Single-Spin Asymmetry A_L (Mid-rapidity)

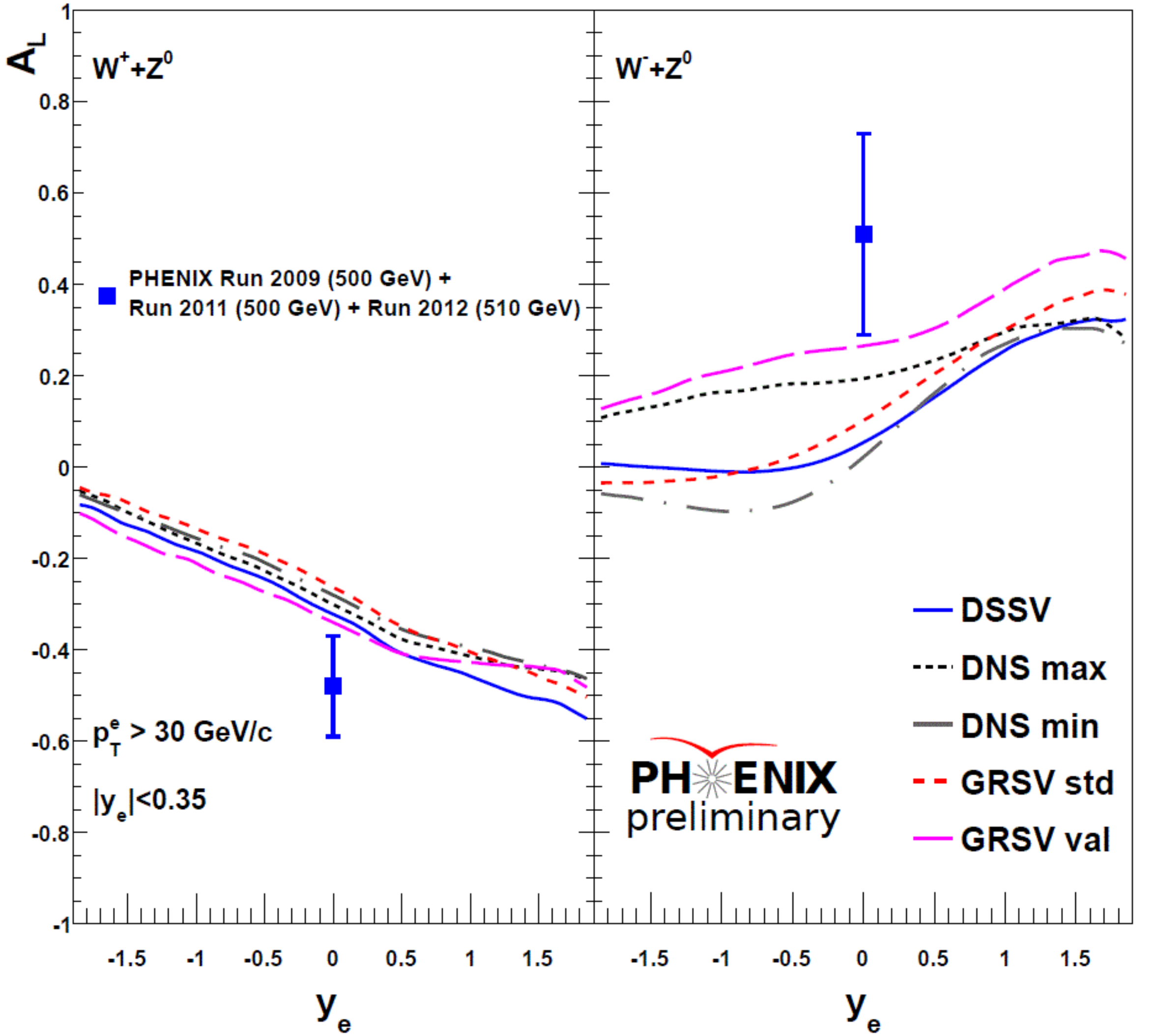
Year	√s (GeV)	∫Ldt (pb^{-1})	Pol. (%)	P^2L (pb^{-1})
2009	500	8.6	39	1.3
2011	500	16	48	3.7
2012	**510**	**23.7**	**55**	**7.2**

(Note: recorded luminosity within |z-vertex|<30 cm)



- Run 2012 Beam Polarization uncertainty $\delta P/P$ = 3.4% (not shown)
- A_L corrected for dilution by background

Mid-rapidity $W^{\pm}$ Single-Spin Asymmetry A_L combined over Run 2012, Run 2011 and Run2009



Within errors, A_L measurements are consistent with the theoretical predictions

Forward rapidity W Measurements

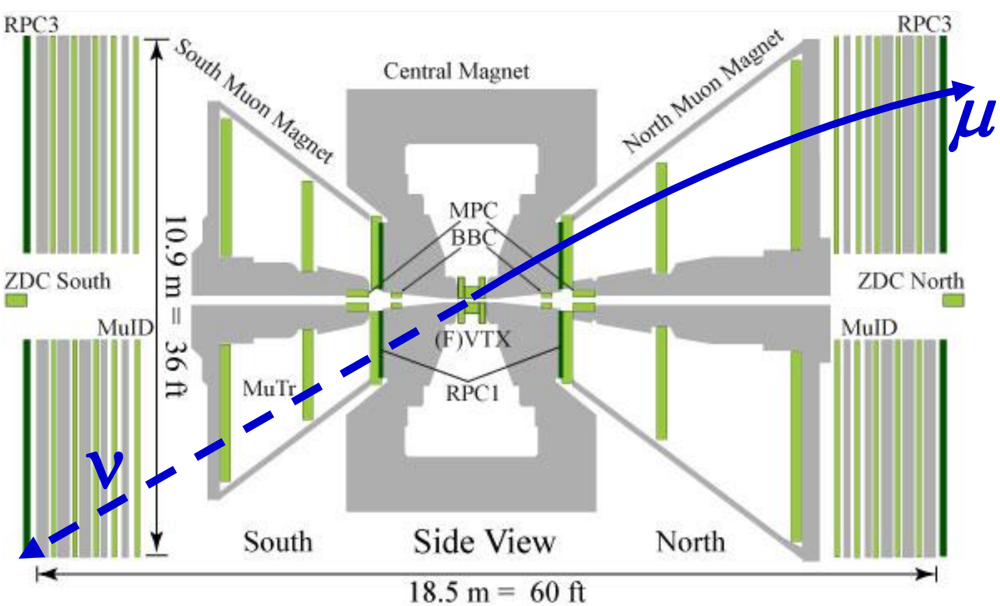
-2.2 < η <-1.2 & 1.2 < η < 2.4

$$p + p \rightarrow W^{\pm} \rightarrow \mu^{\pm} + \nu$$

PHENIX Forward Arm Spectrometers

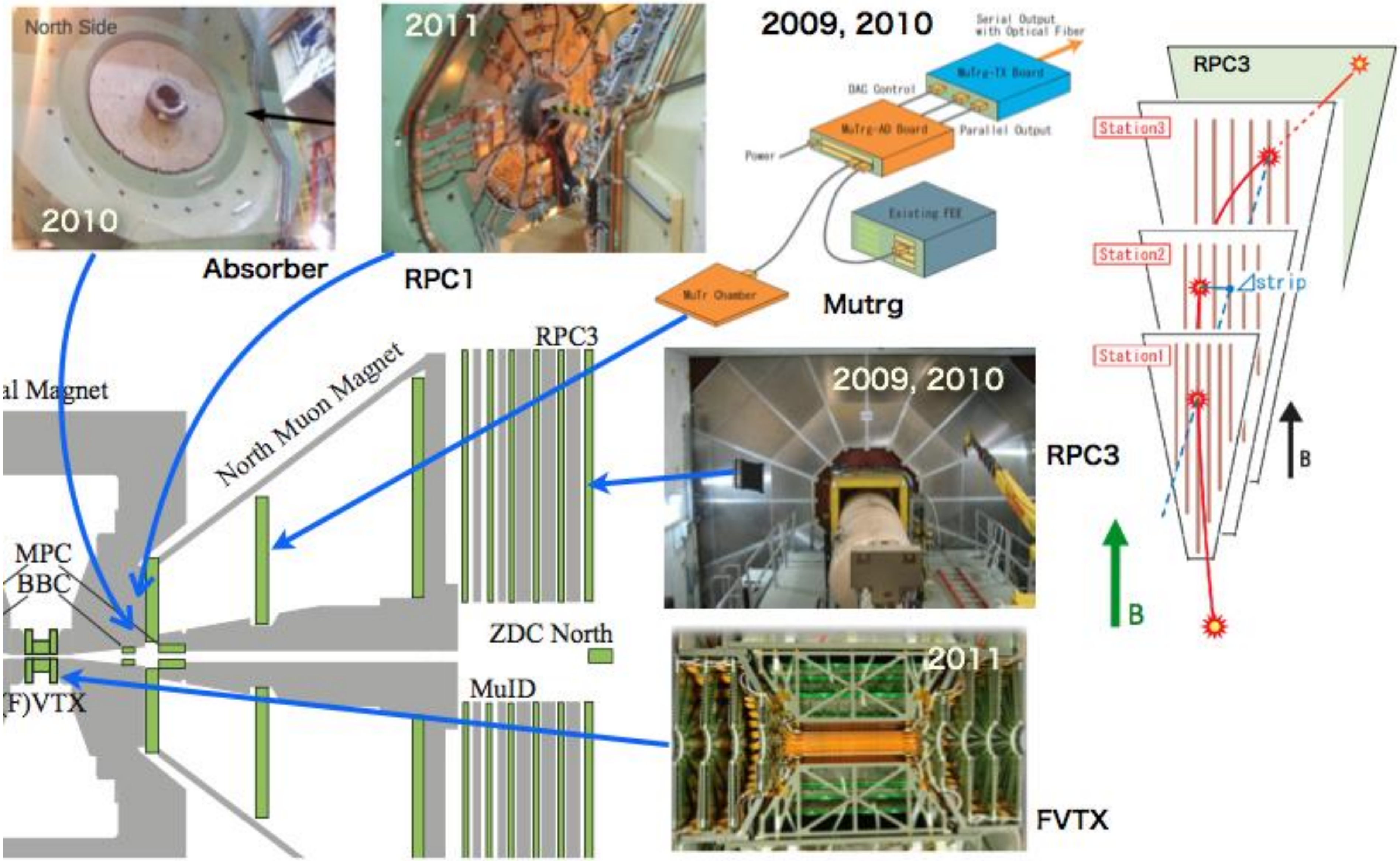
$$p + p \rightarrow W^{\pm} \rightarrow \mu^{\pm} + \nu$$

- $1.2 < \eta < 2.4$ (North)
  $-2.2 < \eta < -1.2$ (South)
- $\Delta\phi = 2\pi$
- Radial B Field



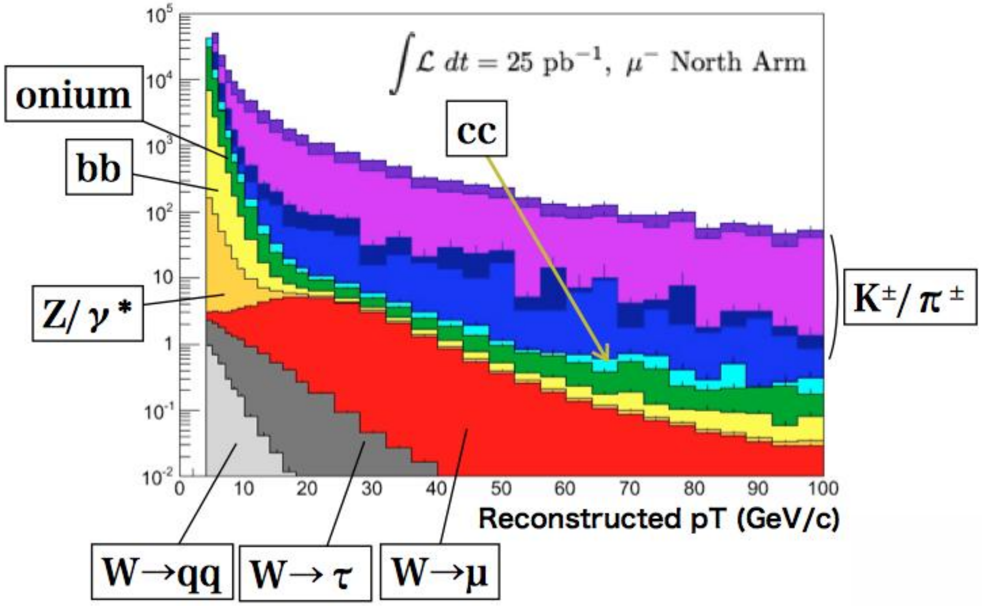
- Fully upgraded in 2012: new upgrades provide trigger rejection to reject low-p muons
- High-pT trigger including RPC: small bending in magnetic field + timing (BBC/RPC)
- =>Trigger on straight-line tracks through the whole muon arm
- Muon Tracker (MuTr): tracking, triggering
- Muon Identifier (MuID): particle ID, triggering
- Resistive Plate Chamber (RPC): particle ID, triggering
- Forward Vertex Detector (FVTX)

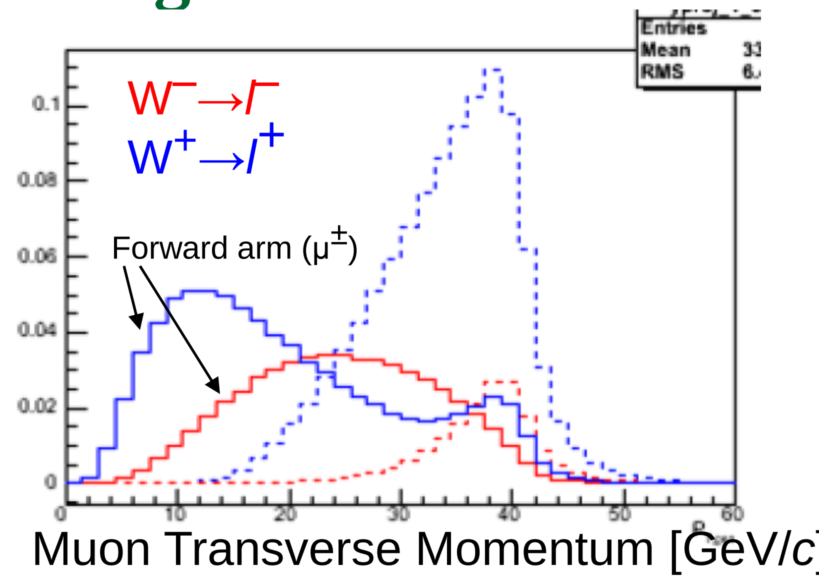
PHENIX Forward Upgrade Program



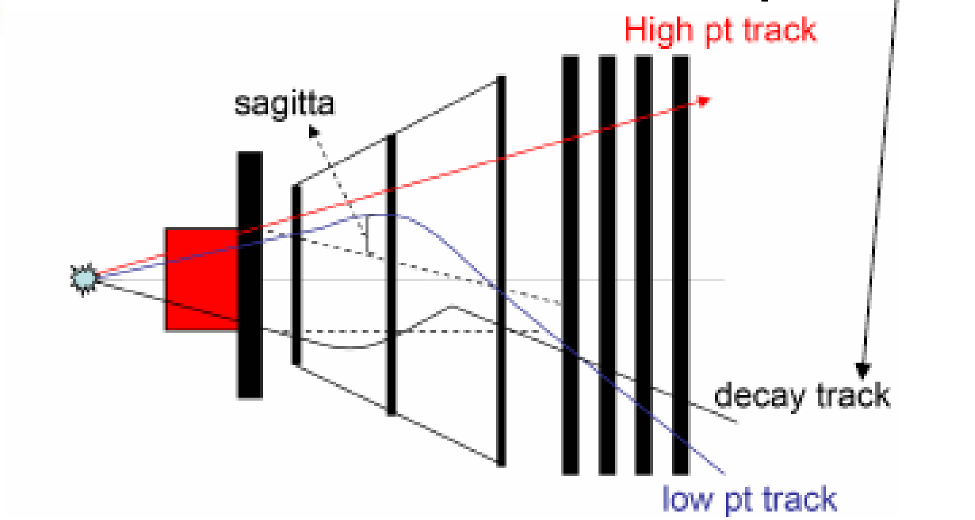
Understanding Backgrounds

No Jacobian peak to help distinguish signal from background level





Dominated background is from misreconstructed low pT hadrons



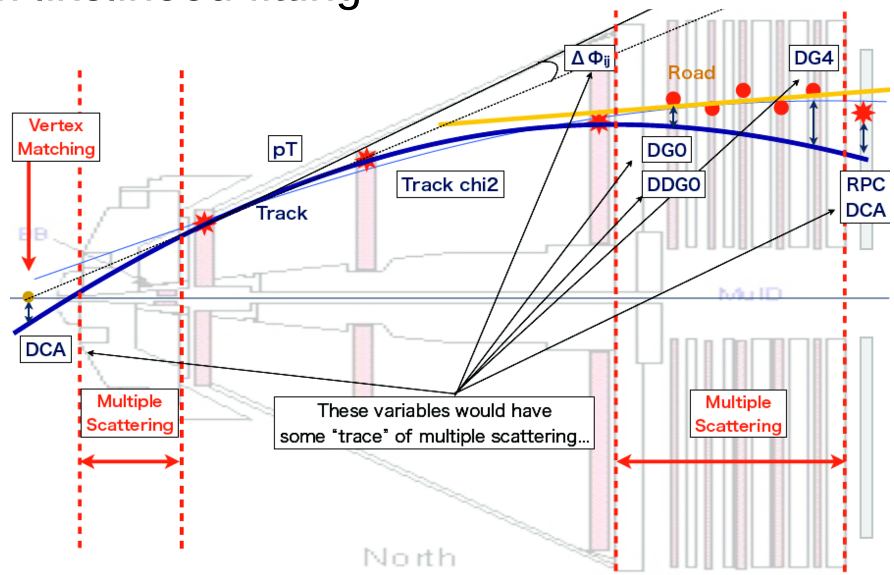
Backgrounds:

- Muon BGs: Heavy flavor, quarkonia (“true” muons, momentum smeared to high pT)
- Hadronic BGs (“fake”)

Signal Extraction in Forward Arm Analysis

Likelihood-based signal selection (2 steps):

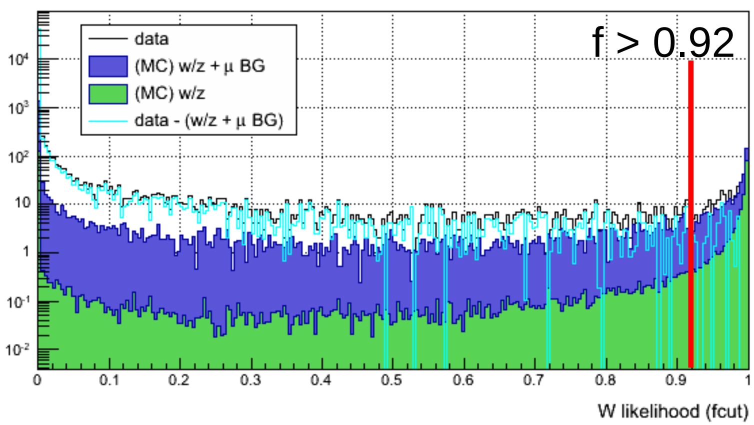
1. Pre-selection: multivariate cut using likelihood ratio
2. S/B ratio extraction: unbinned maximum likelihood fitting



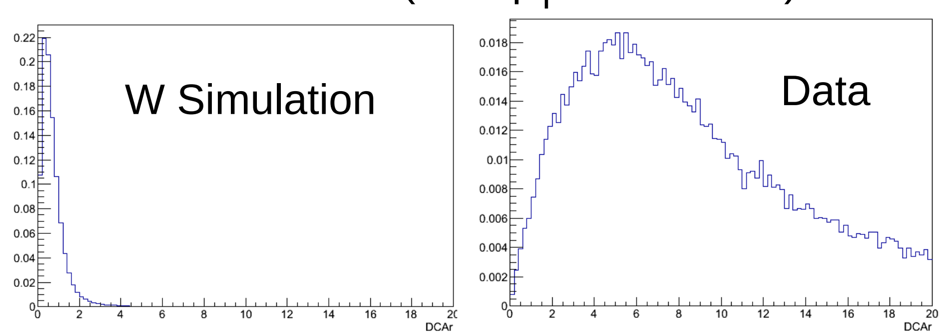
Step 1. Multivariate cut for pre-selection

$$f \equiv \frac{\lambda_{\rm sig}}{\lambda_{\rm sig} + \lambda_{\rm BGs}}$$

$$\lambda \equiv \left[p(\mathrm{DG0},\mathrm{DDG0}) \cdot p(\chi^2) \cdot p(\mathrm{DCAr}) \cdot p(\mathrm{RpcDCA}) \right]$$



DCAr Distribution ($16 < p_T < 60$ GeV/c)



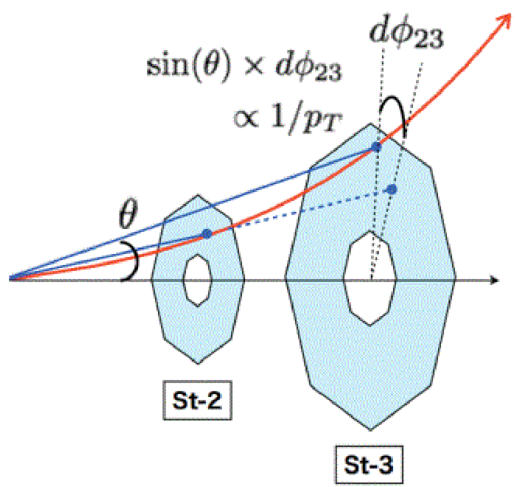
Signal Extraction in Forward Arm Analysis

Step 2.

- Extended unbinned maximum likelihood fitting

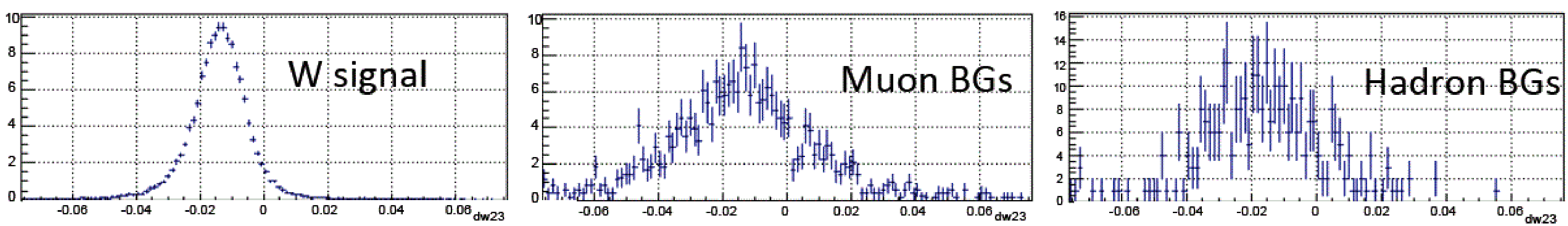
$$\mathcal{L}(\theta|X) \equiv \frac{n^N e^{-n}}{N!} \prod_{x_i \in X}^{N} \left[\sum_c \frac{n_c}{n} p_c(x_i) \right], \quad n = \sum_c n_c$$

- Probability distribution functions extracted from simulation (W signal, muon BGs) and data (hadron BGs) using eta, dw23 (reduced azimuthal bending).

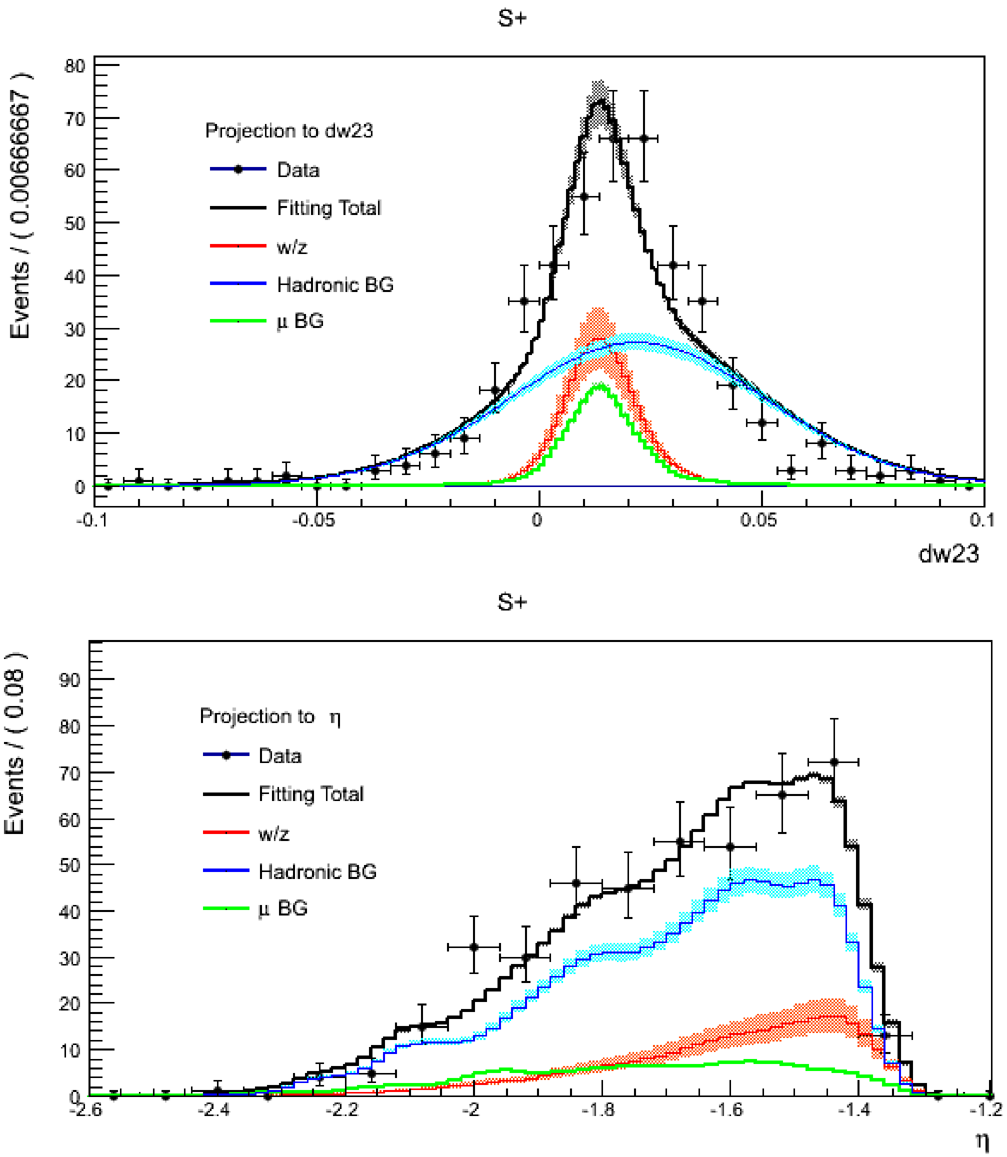


$$\mathrm{dw23} \equiv \mathrm{pT} \times \sin\theta \times \mathrm{d}\phi 23$$

dw23 distributions (16 < p_T < 60 GeV, f > 0.02)



S/B Ratio in Forward Arm



S/B ratio used for the dilution factor

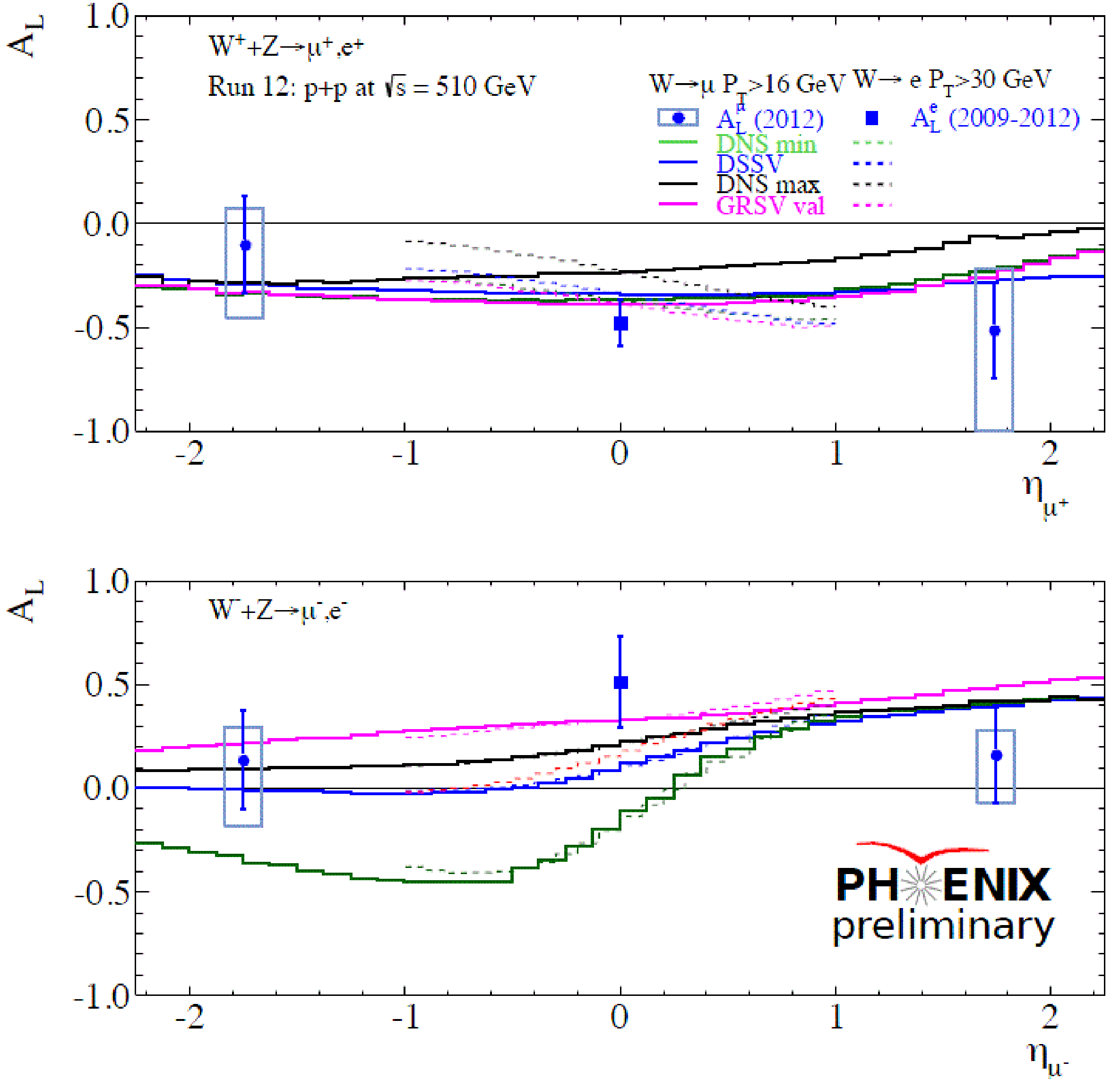
- 1D projections of the 2D unbinned maximum likelihood fit onto dw23 (top) and rapidity η (bottom)
- $16 < p_T < 60$ GeV/c, f > 0.92

S/B ratios:

	South	North
µ+	0.30	0.24
µ-	0.58	0.15

Factor [x0.5 – x2.0] range, as a conservative uncertainty of the S/B

Run 2012 Forward Rapidity $W^{\pm}$ A_L



• Beam combined asymmetries for forward rapidity (along with the mid-rapidity results)

• Boxes are systematic uncertainties from background

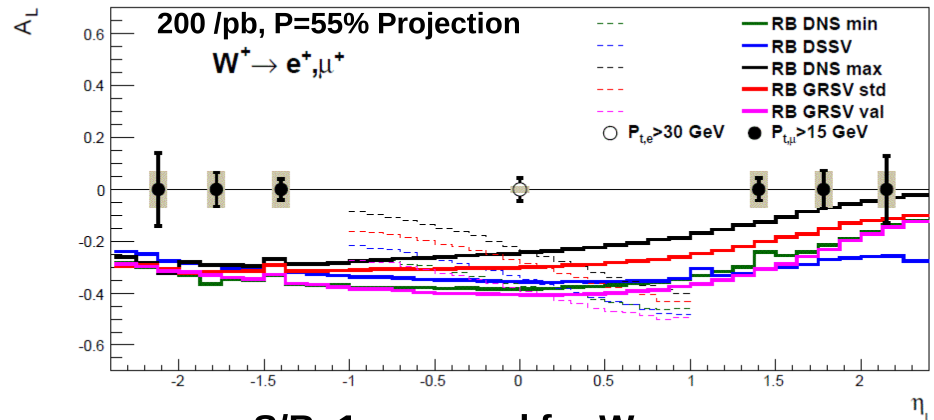
• Run 2012 Beam Polarization uncertainty $\delta P/P$ = 3.4% (not shown)

• Within errors, A_L measurements are in agreement with the theoretical predictions

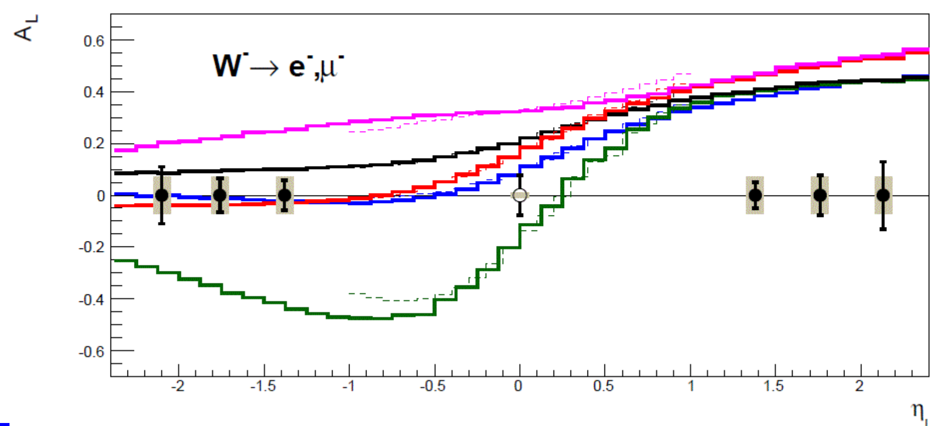
Run 2013 and Expectation of PHENIX W Program

Year	√s (GeV)	∫Ldt (pb^{-1})	Pol. (%)	P^2L (pb^{-1})
2009	500	8.6	39	1.3
2011	500	16	48	3.7
2012	**510**	**23.7**	**55**	**7.2**
2013 (expected)	**510**	**~200**	**55**	**60.5**

(Note: recorded luminosity within |z-vertex|<30 cm)



S/B=1 assumed for W→μ

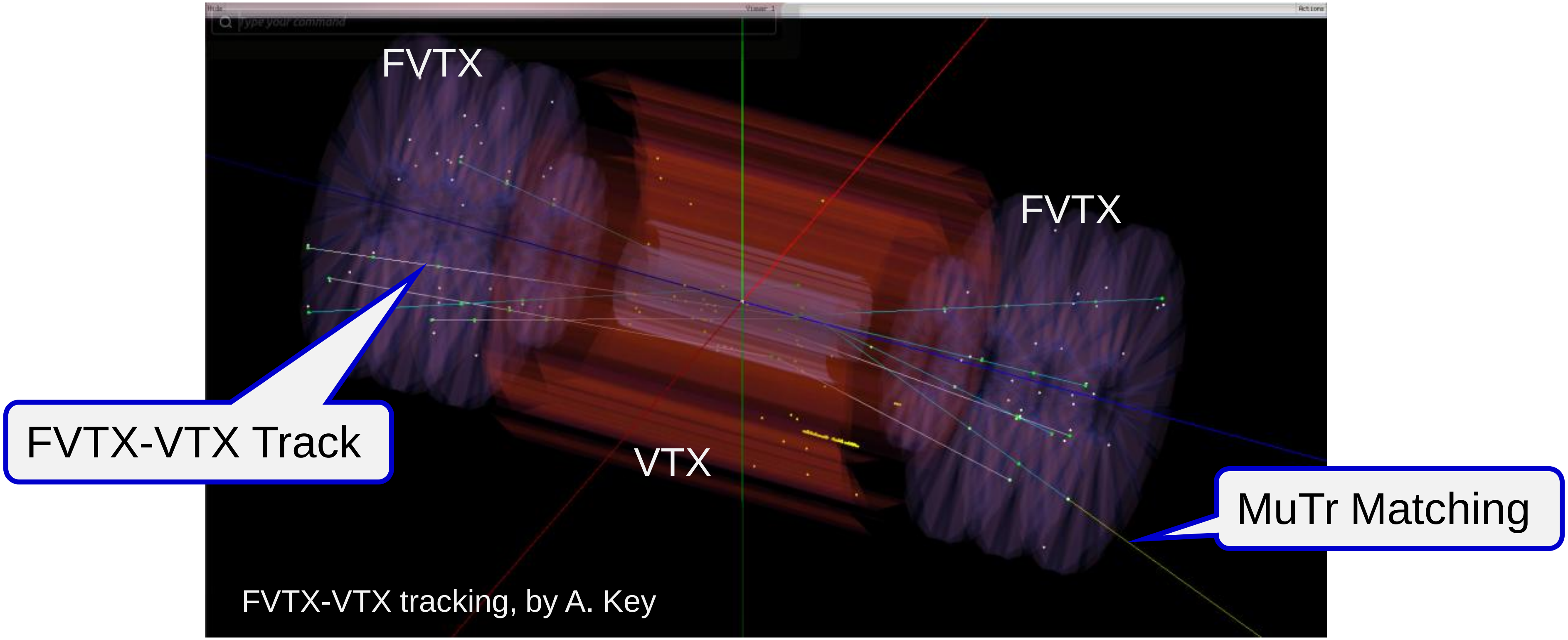


✓ The ongoing Run 2013 is expected to bring us ~150 pb^{-1} of data at 55% polarization giving us opportunity to finalize our W measurements

FVTX is Expected to Contribute on Background Reduction

FVTX covers $1.2 < |\eta| < 2.4$, 2π in φ;

Expected to improve analysis power by
- Precise vertex determination
- Better Tracking



Summary

- ✓ Run 2012:
  - PHENIX collected data more than combined Run 2009 + Run 2011 dataset, also with improved polarization in comparison to Run 2011 and Run 2009
  - Forward arm upgrade is completed
  - In 510 GeV p+p collisions measured $W^{\pm}$ spectra at mid-rapidity and A_L at mid-rapidity and forward/backward rapidity
  - Within errors, A_L measurements are in agreement with the theoretical predictions
  - Improvement of S/B with FVTX is under development
- ✓ Run 2013:
  - Run 2013 is ongoing
  - Run 2013 is expected to bring us enough data giving us opportunity to finalize our W measurements which will result in improved extraction of the flavor separated quark and anti-quark polarized PDFs